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FAA Air Traffic Control Tower Cab Glass Evaluation, Specification and Assessment With Respect to Optical-Visual Characteristics

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Air Force Research Laboratory
Human Effectiveness Directorate
Warfighter Interface Division
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TECHNICAL REVIEW AND APPROVAL

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THIS TECHNICAL REPORT HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION.

FOR THE DIRECTOR

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14. ABSTRACT
The objective of this FAA-funded effort was to determine appropriate optical/visual parameter requirements for FAA tower cab glazing. Provided are recommended values and measurement procedures that include a recommended list of relevant optical parameters, a summary of existing and proposed specifications, recommendations with rationale for the desired minimum (or maximum, as the case may be) allowed value, recommended standard test procedures, the impact on visual capability, and a summary of the sample glazing and shading tests.

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1.0 INTRODUCTION AND BACKGROUND

The overall objective of this effort is to determine the appropriate optical/visual parameters to specify Federal Aviation Administration (FAA) air traffic control tower cab glazing with recommended specification values and measurement procedures. The primary purpose is to develop a recommended specification for air traffic control tower (ATCT) cab glass, specifically insulated glass units (IGUs), with respect to visual capability. Primary parameters of interest are visible light transmission, reflection, haze, and multiple imaging angular separation. Appendix A is a copy of the statement of work (SOW) that governs this report. The organization of this report corresponds to the different sections of the SOW.

2.0 REVIEW OF EXISTING FAA AND RELATED DOCUMENTS (SOW 2.1)

Table 1 is a listing of the documents relating to ATCT cab glazing that were provided by the FAA and the corresponding cab glass transmission and reflection values contained therein. In some cases, the value of transmission and reflection were provided in decimal form (transmission coefficient instead of transmission percentage). All values have been converted to percentages for ease in comparison. It is apparent from looking at the table that there are two sources that have values that are totally inappropriate: those from Billings, MT, and Columbus, OH. Both of these were listed in decimal form in the respective documents and it is suspected that these were either typographical errors or were originally incorrectly converted from percentages to decimal form.

The Billings, MT, document listed the allowed cab glass transmission value as 0.09 (which is 9%) and the allowed reflection value to be 0.02 (which is 2%). Columbus, OH, values were similar (0.08 and 0.02 respectively). These transmission values would be totally unacceptable if the contractor had delivered something just barely within specification. Typical sunglasses are about 15% transmissive so a value of 8% or 9% transmissive would have been extremely dark.

Table 1. Summary of Review of FAA ATCT documents.

Source	Cab Glass Trans	Cab Glass Reflection
Billings, MT - Sec. 8-6.3.3	9% min	2% max
Paine Field (Snohomish cnty arprt) - Sec. 2.2.1	87% min	8% max
DTW FAA-GL-94 3, Sec. 8-6.3.2.2	85% min	No spec
Ft Wayne/ATCT RIG Product Data - Ref. PPG	82%	No spec
Ft Wayne/ATCT Sec. A.1.b.	86% min	8% max
MSP ATCT FAA-GL-1449 Sec. 8-6.3.2.2	91%	No spec
Portland Int'l ATCT - Sec. 2.1.3	90% min	8% max
Columbus, OH ATCT - Sec. 8-6.3.3.1	8% min	2% max
FAA Specification 8800, Rev. 3 – Glazing (Appendix D)	65%	No spec

The reflection values noted in both cases would be nice to achieve, but they are probably not realistic for an insulated glass unit (IGU) consisting of two panes of glass. Ordinary, uncoated glass reflects approximately 4% per surface, which means for an ordinary "clear" piece of glass (index of refraction of about 1.5), one would expect a total reflection of about 8% (4% from the front surface and 4% from the back surface), and for an IGU, one would expect a reflection of about 16% (since there are four surfaces). Some glass manufacturers do offer architectural glass that has been coated/treated such that the reflection value is about 1% per surface (e.g., Pilkington OptiView™ glass[16]). Even this glass would still result in a total reflection value of about 4% for an IGU that has four surfaces that reflect.

Another issue with the documents that were reviewed is that it was sometimes unclear as to whether the specified values pertained to each pane (lite) of glass or to the completed window unit, which may contain more than one pane of glass. Most of the window units are made up of two pieces of glass with an air gap between them (the IGU), although at least one is a laminated product that does not have an air gap in the middle. It is possible to achieve better (higher) transmission values and lower overall reflection values by using a laminated product instead of an air-gap product, but there is a price to pay in terms of the insulating value of the window. Whenever possible, we will note when there is a trade-off with other variables, but our primary focus is on the visual characteristics of the windows (what is the effect on the controller's ability to see?).

With the exception of the Billings, MT, and Columbus, OH, documents, it is apparent that there is reasonable agreement among the specified values. The transmission values range from 82% to 91% although some of these numbers (the 82% value) were actually referencing the transmission of the final, completed window unit, not the transmission of each of the two panes. Specifications must make it clear when one is referring to the values associated with a single pane of glass or associated with the completed product. The recommended specification developed for this effort addresses the optical/visual parameters of the *completed product* (the full window unit).

None of the ATCT specification documents reviewed directly addressed the parameters of haze or multiple imaging (double imaging). However, a separate FAA document that was reviewed was a Quality Assurance (QA) procedure entitled: "ATCT Glass Test Point Description and Double Insulated Glass Unit Assembly Tolerances" (see Appendix B for the original text of this document[12]). This document has no other identifying number or source but, according to James McNamee of the FAA, the document has been successfully used for ATCT cab glass acquisition and testing. Since this QA test uses an "L" shaped pattern to conduct the test, it is referred to as the "L" pattern test in this document. According to Mr. McNamee, field rejection rates for installed ATCT cab insulated glass units dropped from 50% to 10% after this QA test was instituted.

An article published in the Journal of ATC (April-June 1998)[13] written by D. R. Goodall, indicates that this "L" pattern test procedure was devised as a result of increased multiple imaging effects in ATCT cab glass that was a consequence of adding an EMI (electro-

magnetic interference) suppression coating to the cab insulated glass unit. According to Goodall, Fluor Daniel, Inc., conducted a detailed investigation into control tower glass and glazing systems in the 1990's. This investigation was conducted as the result of EMI in the ATCT cab caused by the installation of the National Weather Service WSR-88D radars. According to Goodall, the solution to the EMI problem was to incorporate a product called Datastop distributed by Tempest Security Systems, Inc[20]. Tempest Security Systems, Inc., of Troy, Ohio, is the exclusive distributor of Pilkington Datastop glass. According to the Tempest Security Systems web site, the glass has been fabricated in both laminated and sealed insulating unit products. However, the Datastop product also decreases the insulated glass unit transmission coefficient and increases the reflection coefficient of the glass surface to which it was applied, based on the table of values posted on their web site.

The increase in reflection coefficient led to increased complaints and in-field rejection of ATCT glazing units that incorporated the Datastop product. The basis for the complaints was the occurrence of double images when viewing light sources through the glazing unit at night. Appendix C provides background on how these multiple images are formed and why insulated glass units (IGUs) and coatings on IGUs enhance the formation of unwanted secondary images.

In addition to reviewing the FAA-related documents noted above, we also reviewed the relevant American Society for Testing and Materials (ASTM)[1,2,3,4,5,6] and National Fenestration Rating Council (NFRC)[15] documents referenced in the FAA materials.

Most, if not all, of the FAA documents call out ASTM C1036-06[1] as the Standard Specification for the type of glass used in the cab windows. ASTM C1036-06 provides an extensive listing of different kinds of defects that can occur in flat glass but does not include any test procedure for measuring the transmission and reflection values of the glass. Instead, it calls out NFRC 300[15], Procedure for Determining the Solar Optical Properties for Simple Fenestration Products (Section 2.2 of ASTM C1036-06). A review of NFRC 300[15] revealed that it also does not describe a test procedure for transmission and reflection but simply calls out (NFRC 300, Section 6.1) another ASTM document for that, namely ASTM E903-96[3]. ASTM E903-96 is directed at primarily characterizing the transmission and reflection of solar radiation more so than just the visible spectrum *and it was withdrawn in August of 2005 with no replacement*.

The end result is that ASTM C1036-06 does not lead to a currently viable, approved test procedure for measuring visible transmission and reflection coefficients. The chairman of the subcommittee in charge of ASTM C1036-06 has been contacted and was unaware of the blind end that is a result of ASTM C1036-06 referencing NFRC 300, which references ASTM E903-96, which has been withdrawn. To date, this issue has not been resolved despite several months of effort to motivate the parties.

An alternative to the ASTM C1036-06 pathway for measuring transmission and reflection values is to reference ASTM D1003-00[2] (for transmission and haze) or ASTM F1316-90[6] (for transmission) and ASTM F1252-89[5] (for reflection measurements). The

latter two were developed for aircraft transparencies but can easily be applied to the measurement of flat glass.

In any event, it is highly desirable to make sure that the measurement procedures for any specification values called out in the specification document are based on viable, documented, and currently accepted methods.

In addition to the documents listed in Table 1, an FAA report (FAA-RD-72-65)[10] titled, "Study of reduction of glare, reflection, heat and noise transfer in air traffic control tower cab glass" by J. Michael Clinch was reviewed. This report documents some of the issues and potential mitigation methods associated with ATCT cab glass reflections. In particular, they note the value of addressing overall ATCT cab geometry design, ceiling colors, interior lighting, and interior fixture characteristics in preventing light source reflections. The basic concept is to try and insure that there is no emitted or reflected light source that is in a reflection geometry with respect to a controller's viewing position when looking through the cab glass windows. Since this FAA report by Clinch covers that aspect of the mitigation methods to reduce reflection problems, it will not be repeated here.

The Clinch report also provides a basic primer on coatings to reduce the reflection coefficient of an air-glass interface by coating the surface with an appropriate thickness of transparent material to produce an interference-based, anti-reflection treatment. This is basically the method used by some manufacturers to produce glass products with reduced reflection coefficients (e.g., Pilkington OptiView™ glass, Zamilglass[21]). These surfaces are not as impervious as clear, uncoated glass and require a certain amount of care in handling and cleaning (see Pilkington Technical Notes ATS-182 from their web page).

3.0 MEASUREMENTS OF SAMPLE MATERIALS (SOW 2.2)

AFRL/HECV (Wright-Patterson AFB, OH) measured the transmission, reflection and haze values of one cab glass sample (two panes of glass with intervening air gap) that was provided by the FAA. Haze is a phenomenon caused by light scattering randomly from the material. In general, clear glass exhibits extremely small haze values unless it is covered by a film of material (such as dust or smoke particles). One would expect clean, clear glass to have a haze value of 0.1% (the smallest value measurable with our equipment) or less.

The one piece of cab insulated glass that we measured showed a haze value of 3.5% (see Figure 1). A visual inspection of the sample revealed that most of the light scattering causing the haze was on the inside surfaces of the window (the surfaces at the air gap – see Figure 1; enlarged image to right). If this was supposed to be a sealed air gap, it is somewhat disturbing that there was this high a value of haze caused by a build-up of dust/debris on the air gap surfaces of the glass.

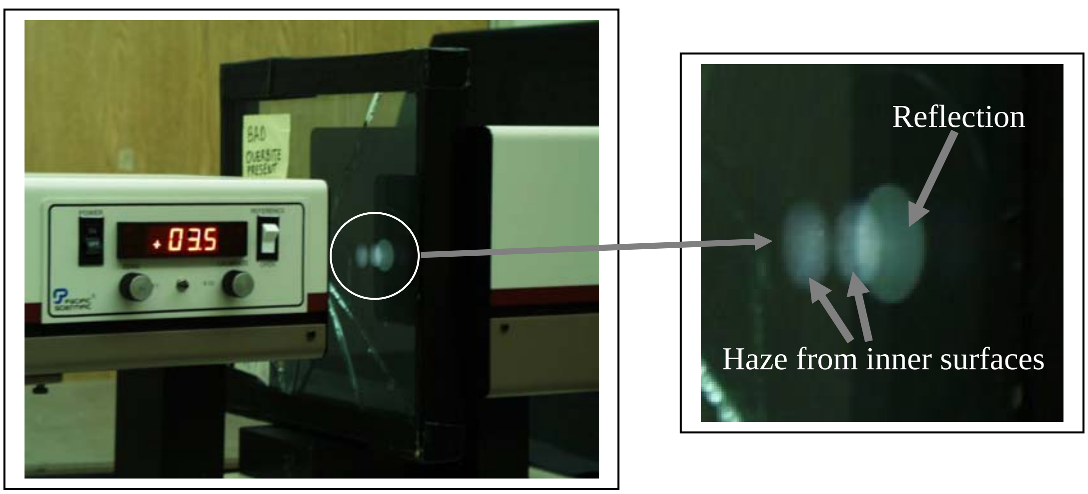

Figure 1. Haze measurement using ASTM Standard Test Method D1003-00.

The transmission was measured at several locations using ASTM D1003-00. Transmission values varied from about 65% to 67%. This is considerably lower than any of the specification values in the FAA-provided documents with the exception of the last one (FAA Specification 8800, Rev. 3 Glazing). The dust within the air gap could have reduced the transmission value by a few percent, but was not sufficient to account for the difference between the measured values and the specification values found in the FAA documents. However, if this sample was coated with an EMI protective coating as in the Datastop product previously discussed, then the reduced transmission makes sense.

The reflection percent for the entire window was also measured using the test procedure as described in ASTM F1252-89. Since there were a total of four air-glass interface surfaces, one would expect to see a total of four major reflections from the FAA-provided ATCT glass sample, which is what was observed. Figure 2 shows the basic setup that

was used to measure the reflection coefficient (in percentage). Figure 3 is a close-up of the reflected image showing the four overlapped reflections. The overall reflection percentage is determined from the area where all four reflections overlap. The reflection of the ATCT glass sample was found to be about 11.3 percent. Since the reflection and transmission percentages do not add up to 100% (67% + 11.3% = 78.3%), it is apparent that there is some scatter (the 3.5 % haze measured) and some absorption taking place in this sample.

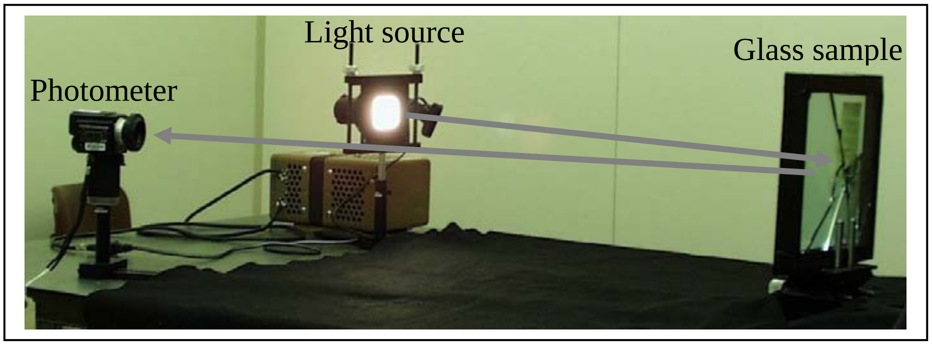

Figure 2. Basic geometry of setup to measure ATCT cab glass reflection percentage.

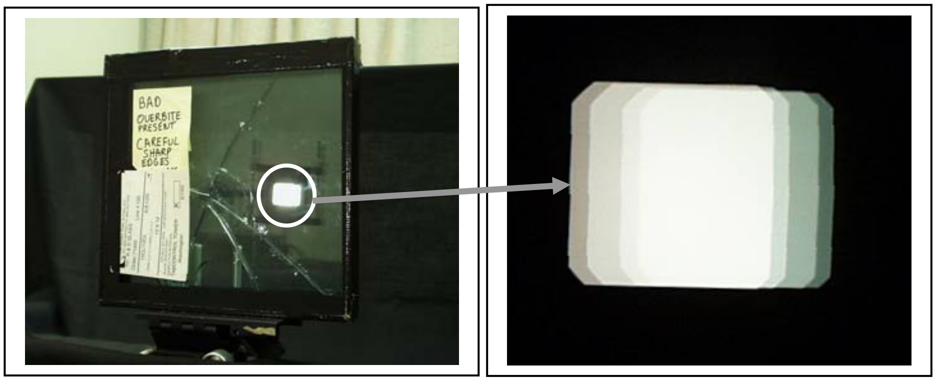

Figure 3. Multiple reflected images as seen from the position of the photometer.

The FAA also provided four samples of the "pull-down" shade material. All four samples are from the IND (Indianapolis, IN) installation. The transmission coefficient of all four samples was measured using the procedure described in ASTM F1316-90. All four samples had a visible light transmission value of about 4% for a 2856K incandescent light source.

The reflection coefficient of one of the samples was measured to be about 5.7% using test method ASTM F1252-89.

FAA specification E-2740b[11], section 3.1.3.1 states that the visible transmission of a shade should not exceed 6% (no lower boundary is provided – this is a deficiency in this specification). Since this material measured 4% transmission, it was well within specification.

The current manufacturer of the shade material was contacted (Plastic-View[17] of Simi Valley, CA, (805) 520-9390). According to the manufacturer, their product is used in about 98% of the ATCT cabs in the US. Their company is mentioned by name in the USAF Air Traffic Control Tower Design Guide[8]. Plastic-View states that their product is "a neutral smoky grey" and transmits about 4% of the visible light spectrum, which is exactly what we measured. The manufacturer also stated that they recommend washing and polishing (with a "plastic cleaner") the shades on a monthly basis, but they did not have a recommended procedure. They also suggested the shade should be replaced every five to seven years depending on usage and location. One last recommendation from the manufacturer was to keep the shades closed at night for those towers that are not in operation during nighttime hours to conserve cab heat.

4.0 OPTICAL/VISUAL PARAMETERS OF INTEREST (SOW 2.4)

This section provides a brief description of each of the optical/visual parameters addressed in this document and what impact it can have on visual capability.

4.1 Transmission

ASTM F1316-90 defines transmissivity (transmission coefficient) as "…the ratio of the luminance of an object measured through the [transparent] medium to the luminance of the object measured directly." This test procedure is based on methods developed by the US Air Force for aircraft windscreens[19]. Luminance is the optical parameter that most closely represents the human visual perception of *brightness*. The two terms are often (incorrectly) used interchangeably. However, to be technically correct, *luminance* is what is measured and *brightness* is what is subjectively perceived. Luminance is typically measured in units of foot-Lamberts (fL) or candela per square meter (cd/m^2). The electro-optical device used to measure luminance is a photometer, which employs a light sensitive detector and filter system that closely matches the spectral sensitivity of the human eye.

The transmission coefficient per se, does not affect visual performance. It is the *combination* of the transmission coefficient of the window glass and the luminance of the scene under observation that can affect visual performance. In general, one would like to have as high a transmission value as possible to minimize the effect on visual capability when viewing out of the ATCT cab at night. However, the eye is a *logarithmic* detector, which basically means that there is a non-linear relationship between light level and visual capability. As an example, if the scene were reduced in luminance by 50% one would not expect visual performance to drop by 50%; the loss in visual performance may only be a couple percent or nothing (depending on the condition of the observer's eyes and the starting luminance level).

The transmission value for clear (non-tinted) windows is primarily a function of the number of air-glass surfaces that are present in the glazing. Although there are coatings and treatments that can be applied to glass to reduce reflections, and thereby increase transmission, (e.g., ½ inch Pilkington OptiView™ glass with reflection of 1.6% and

transmission of 89%), it is not possible to significantly improve transmission values in any practical fashion. Even the Pilkington OptiView™ glass noted above would have an overall transmission of 0.89 times 0.89 or about 79% for an insulated glass unit composed of two panes of the glass (without the EMI coating). It should be noted that Pilkington OptiView™ glass is actually composed of two panes of glass laminated together with clear polyvinyl butyral (PVB). The outer surfaces of the two layers of glass are coated/treated with Pilkington's proprietary pyrolytic surface process to obtain the lower reflection properties.

One should not be overly concerned by the transmission value by itself; it is quite often necessary to trade it off for other, more desirable features (e.g., electro-magnetic interference (EMI) protection). A completed window unit transmission of about 80% is reasonable for *uncoated* (no EMI protection) insulated glass (two panes with air gap) using high-transmission glass such as PPG's ultra-clear Starphire ½ inch thick glass[18] with a visible transmission of 91%. Sixty-five percent is not an unreasonable transmission value for a completed, EMI-coated insulated glass unit (the EMI coating reflects a certain amount of light thereby reducing the transmission value). Note that low emissivity (low-E) coatings can also have an affect on the visible spectrum transmission and reflection values as well. Laminated glass has no air-glass interface surfaces and, therefore, should be capable of higher transmission values than insulated glass units.

The currently referenced standard for measuring light transmission, as previously noted, is ASTM E903-96. This procedure uses an integrating sphere and is primarily concerned with determining solar radiation transmission through the glass. It should be noted that integrating sphere methods of measuring transmission capture essentially all of the transmitted light and include all of it in the measurement/calculation for the transmission coefficient. However, if the transparent medium being measured also scatters light (related to haze; see section below), then this scattered light is also included in the transmission calculation. If it can be ascertained that the glazing under test has extremely low haze values as measured by ASTM D1003-00 (e.g., less than 0.5 percent), then ASTM E903-96 is a reasonable means of measuring visible light transmission. However, if haze values are noticeable (i.e., more than 0.5 percent), then one might want to consider using the ASTM F1316-90 test method to measure the transmission, as this method is designed to measure only the useful (unscattered) transmitted light.

There has been some interest in recent years regarding the use of night vision goggles (NVGs) in air traffic control towers, both military and civilian. NVGs are already being used in limited, non-military aviation such as police departments. It may therefore be of interest to also know what the NVG-weighted transmission coefficient is for ATCT cab glass in the event that NVGs are used in towers in the future. ASTM F1863 Standard Test Method[7] was developed to measure the NVG-weighted transmission of aircraft windscreens and could easily be applied to ATCT cab glass. One would need to know the spectral sensitivity of the NVGs selected for use in the ATCT cab prior to making this measurement. Most likely, Class B or Class C NVGs would be used in the ATCT cab since they permit compatibility with full-color displays.

4.2 Reflection

Reflection from air-glass surfaces or coated surfaces is another issue in glazing products. Although it is possible to reduce reflections through coatings or treatments, it may not be practical to do so. In general, one can figure that each surface of a glazing product will reflect approximately 4% of the light incident on it. However, at least one glass manufacturer, Pilkington[16], claims to have a commercially available architectural glass product (OptiView™) that reflects only 1.6% (total) of the light (for 12mm thick glass). This is substantially less than the 8% one expects from ordinary float glass. In addition, Pilkington states that the visible transmission for this 12mm thick product is 89%. The haze value was not quoted.

Another glass manufacturer, Zamil glass (ZGI)[21], states that they can achieve less than 3% visible reflection using their anti-reflection glass coating/treatment.

The reflection coefficient can affect visual capability in at least two significant ways. The first occurs when viewing light sources outside of the ATCT cab at night. If the surfaces of the insulated glass unit are not perfectly flat and parallel, then one will see one or more reflected images in the vicinity of the light source being viewed through the window. This effect is most evident at night when looking at light sources, which corresponds to a *super contrast* situation. It is usually invisible in daytime because the overall background luminance washes out these secondary images. At night, these secondary images can be annoying, distracting, and/or confusing depending on the distribution of light sources being viewed through the window and the characteristics of the images. The angular separation of the images and the relative intensity of the secondary images compared to the primary light source image are the two factors that are used to characterize this effect. It is very difficult to reduce the intensity of the secondary images to a point where they are not visible at night, although anti-reflection glass can help. It is possible to more effectively address the degree of angular separation of the secondary images from the primary image. This latter parameter is the subject of the multiple imaging section and test procedure described below. If one could successfully reduce the intensity of the secondary images to below visual threshold, then one would not need to address the multiple imaging factor as described below. However, as is the case with current technological levels, if one cannot reduce the intensity to below threshold, then the only way to mitigate this effect is through techniques that keep the secondary images close to (within a specified angular separation) the primary image. Appendix C addresses the multiple imaging issue in more detail.

From the Goodall (1998) article and the QA “L” pattern test, it is apparent that controller acceptability tests were done at the FAA Test Center to establish an acceptable criteria for “marginally acceptable” windows that exhibited noticeable multiple imaging (or double imaging – several terms are used to described this same phenomenon). Based on the acceptance criteria described in the QA document and the multiple imaging creation mechanism described in Appendix C, it is possible to calculate the acceptable level of angular separation between the primary image and the secondary (double) image.

From the QA document, the 6mm acceptance criterion value (see Appendices B and C) corresponds to about 5.2 minutes of arc, and the 8mm criterion value corresponds to about 6.9 minutes of arc. These are also the maximum allowed tilt angles between the two reflecting surfaces (e.g., the inner and outer panes of glass in an insulated product) for the two identified viewing zones. The observed angular separation of the primary image from the secondary image for objects viewed outside the cab is equal to twice the tilt angle between the glass surfaces. This means the secondary image may appear a maximum of 10.4 arc minutes away from the primary image in the primary viewing area and a maximum 13.8 arc minutes away for the boundary viewing area. From the description provided in the QA documents, these values were evidently found to be "marginally acceptable" for their respective viewing zones and, therefore, serve as the acceptance criteria values. These allowed multiple imaging separation values are very similar to acceptable values found for military aircraft windscreens (Kama et al., 1987)[14].

The second way in which reflection can interfere with controller's vision is light sources within the cab (or direct sunlight that enters the cab), which can cause disturbing reflections during either day or night operations. The effects of these reflections can be a loss of contrast of the image being viewed, a masking effect of a competing image, or glare. The two ways to mitigate these effects are to reduce the reflection coefficient or to design the ATCT cab to reduce or eliminate the probability that any light source (artificial or natural, direct or indirect) can produce a reflection in the pathway of a controller's view out of the cab windows.

4.3 Haze

The primary visual effect of haze is a loss of contrast produced by a veiling luminance. However, if the window is not illuminated by some significant direct source of light (direct sunlight or artificial light), relatively low levels of haze (a few percent) would most likely not be noticed. If the light source is sufficiently intense, then the light scattered by the haze produces a veiling luminance in the controller's line of sight through the window, thereby reducing the contrast of the scene being viewed.

Clear glass, and even coated glass, typically has extremely low values of haze (on the order of tenths of a percent). However, laminated glass, worn glass, or glass with coatings that have been worn (micro-scratches) can produce elevated levels of haze. The FAA-provided sample of ATCT cab glass measured in the previous section (Figure 1 enlargement) shows what can happen to the haze value of glass if it is not properly cleaned. Since the effect of haze depends on the haze value measured, the intensity of the illuminating light source, and the luminance of the scene being viewed, it is difficult to establish a maximum allowed value with any great conviction. As with the other parameters (transmission and reflection), the value might need to be considered in light of trade-offs necessary to achieve other desirable features. For example, laminated glass should result in lower reflection values and higher transmission values, but the plastic and/or adhesives required to laminate the glass might well have a noticeable level of haze (which may or may not be acceptable).

4.4 Multiple Imaging

This parameter has already been briefly discussed in Section 4.2 on Reflection and is discussed extensively in Appendix C. The unique aspect of this parameter is that it is one that is most susceptible to engineering and manufacturing processes and procedures. The three parameters previously discussed are very limited by technology, processes, and materials that are currently available. The multiple imaging parameter, as characterized in the Appendix B Quality Assurance procedure, actually provides a means of engineering to obtain results within tolerance.

Ordinary float glass is very flat and the two surfaces are normally very parallel to each other. This is why a single sheet of float glass is unlikely to produce any noticeable multiple imaging effect even though it has a very noticeable reflection percentage. However, the very large insulated glass units that are composed of two lites of float glass suffer from the potential of mechanical forces causing the two sheets of glass to bend enough to produce geometries that cause multiple images as described in Appendix C. Specifically, difference in air pressure between the air within the insulated glass unit and the outside ambient air pressure can cause the two glass plates to bulge outward from each other or sag inward towards each other. It is this relative curvature of the two panes with respect to each other that produce different levels of angular separation of the primary image from the secondary image, which also vary depending on where within the IGU you are looking. The procedure described in Goodall (1998) that uses a small tube to equalize air pressure, is the tool that allows one to adjust the air pressure inside the IGU so that it equals the ambient air pressure outside. Using this adjustment should make it possible to greatly reduce any multiple imaging angular separations.

However, there is a potential problem with this procedure. If the air pressure is adjusted to equalize with the ambient air pressure after the unit is installed and then the small air tube that allows for this equalization is closed off, then the IGU is only correct for that specific ambient air pressure. If the ambient air pressure changes (up or down), then the two glass sheets will sag or bulge possibly creating an objectionable degree of multiple imaging separation. Even if dry air is used to make this adjustment, there is a concern that every time the air pressure is equalized, there is a chance for microscopic particles or moisture to enter the air gap that can result in fogging or haze effects. It is unclear from the materials that have been reviewed as to how often the air pressure equalizing tube is employed to reduce multiple imaging once the IGU has been installed in the ATCT. However, discussions with Ian Waterman of Tempest Security Systems indicate the pressure equalization method employed in the towers that used the Datastop glass produce used a dry air reservoir connected to the air-gap via the small tube to continuously maintain pressure equalization between the outside ambient air and the insulated glass unit.

4.5 Other Optical/Material Parameters - Scratches, Minor Optical Defects, Polarization

Most of these parameters are covered in ASTM C1036-06 and typically do not interfere with visual performance. Polarization is not a topic covered in ASTM C1036-06 and should not be an issue. Although clear blue sky can be up to 80% linearly polarized, this has little or no effect on vision provided there is not a polarizer elsewhere in the visual path. As long as the IGU does not exhibit polarization effects (which can occur with some tempered glass and with birefringent plastics), polarization should not be a factor. If there is the potential that the IGU could have polarization effects, it can be viewed through a linear polarizer with a polarized light background to make sure there are no birefringent induced color effects or mottling due to uneven thermal tempering.

5.0 RECOMMENDED SPECIFICATIONS (SOW 2.3)

The suggested specification parameters of transmission, reflection, and haze are compromises between what would be ideal from a visual standpoint and what makes sense from a physical materials and manufacturing technology standpoint. Ideally, from a human visual standpoint, one would like the IGU transmission to be 100% and reflection and haze to be 0%. These values are not obtainable. Therefore, the philosophy behind the suggested parameter values is to achieve a reasonable trade-off between what is ideal and what can be achieved. Since these parameters are not independent of each other and since there are trade-offs in desirable values, the suggested specification values for these parameters depend on the selected features of the IGU (specifically, the anti-reflection coating/treatment, low-E coatings, and the EMI coating). Trade-offs with thermal insulation and solar loading also need to be considered, but are beyond the scope of this effort. The suggested specification values are for the completed window unit.

5.1 Transmission (visible)

The visible light transmission shall be a minimum of 65% as measured by ASTM E903-96, ASTM F1316-90 or ASTM D1003-00.

Note: It might be possible that a double-insulated-glass unit with Low-E coating and EMI coatings could achieve higher visible transmission values, but the selected value above should have minimal impact on controller’s visual ability for night viewing and is in line with measurements made on the sample IGU and the contents of FAA specification 8800.

5.2 Reflection (visible)

The visible light reflection, measuring from the surface that is interior to the ATCT cab, shall have a maximum of 15% as measured by ASTM F1252-89.

Note: It might be possible to achieve lower reflection values through the use of anti-reflection coatings/treatments on some surfaces of the glass. Based on FAA experience,

it is more important to be within the specified maximum allowed angular separation values embodied in FAA QA procedure associated with multiple imaging (the "L" test).

5.3 Haze

The ATCT cab glazing shall have a maximum haze value of 0.7% as measured by ASTM D1003-00.

Note: Laminated glazing may have higher haze values due to the materials used to laminate the layers together. Higher haze values could be acceptable if one achieves higher transmission values and lower reflection values as a trade-off. In any event, haze values shall not exceed 2.0%.

5.4 Multiple Imaging (double imaging)

The ATCT insulated glass unit shall pass the requirements of the FAA quality assurance test for multiple imaging (the "L" test - see Appendix B) or the modified test as described in Appendix C. The viewing geometry for these tests should maintain the viewing position as close as possible to the target pattern generator position (see Appendix C for details).

6.0 POSSIBLE PERIODIC FIELD TESTS TO ASSURE QUALITY (SOW 2.5)

No data or materials were provided by the FAA relating to periodic field testing of ATCT cab glass or pull-down shades quality with the exception of the multiple imaging QA test, (Appendix B), which can be used as a periodic quality test.

6.1 Multiple Imaging (double imaging) QA test

The multiple imaging QA test using the "L" pattern is suitable for periodic field tests in the ATCT cab to determine if the glazing units need to have their air pressure "equalized" with the ambient air pressure. This test could be applied when needed if controllers operating at night find the multiple imaging has gotten worse or is objectionable. In any event, the test could be performed annually. It is suggested the modified test described in Appendix C be considered since it does not require orienting the "L" pattern for the specific reflections that occur, and the circular disk pattern is easier to fabricate than the multi-colored "L" pattern.

6.2 Backscatter haze (clean window, use flashlight, compare images)

A field test of this nature could be used to determine when the cab windows are in need of cleaning or when there has been a build-up of haze (dust/debris) on the interior surfaces of the glazing units. This is a qualitative test that could perhaps be further developed to become a quantitative field test[9]. The basic test is to use a flashlight to illuminate the cab glass from inside the cab (at night) and look carefully at the amount the surfaces of the two glass panes "light up" from scattering by dust/dirt/debris on their

surfaces. As a reference point, the surface of the glass accessible to the controllers on the inside of the cab (surface number 4 in the insulated glass surface numbering convention) should be thoroughly cleaned and compared to the “light up” effect seen on the other three surfaces. If the IGU has a well-sealed cavity and there has been little or no air exchange with the exterior world, then the two inner surfaces (surfaces 2 and 3) should exhibit essentially no “light up” effect when the flashlight is shined through the unit. The right hand picture in Figure 1 shows this “light up” effect for the two inner surfaces of the sample of insulated glass provided by the FAA. This picture shows only two “light up” discs because the outer surfaces (1 and 4) were thoroughly cleaned before the sample was measured for haze. If the outermost surface (number 1) is in need of cleaning it will “light up” as well.

6.3 Pull-down shade inspection

The interior “pull-down” shades can become scratched with multiple cleaning, aging and use over the years. The manufacturer (Plastic-View of Simi Valley, CA) recommended replacing the shades every 5 to 7 years. One way to determine the condition of the aged shades compared to what they looked like new is to request from the company an 8” by 10” sample of the material and visually compare it to the aged shade in the cab. The evaluator should look through both the aged shade and the new sample to compare visual effects during a critical time of day and under difficult sunlight geometry conditions. This would most likely involve looking through both materials (side-by-side) in the general direction of the sun while it is low on the horizon and check the visibility of objects on the ground in the general direction of the sun. A second critical visual task might be looking for aircraft in clear blue sky in the general direction of the sun, again looking through both materials (the new and the old) to see if there is a difference in visual quality. This is obviously also a subjective assessment, but could help in determining whether or not the shade should be replaced.

7.0 REFERENCES

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17. Plastic-View ATC, Inc., 4585 Runway, Suite B, Simi Valley, CA 93063. http://www.pvatc.com

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20. Tempest Security Systems, Inc., P.O. Box 584, Troy, OH 45373. http://www.tempestusa.com

21. Kuwait Zamil Glass Industries, P.O. Box 36450, RAS 24755, Kuwait. http://www.zamilglass.com

APPENDIX A

Statement of Work (SOW)
for
FAA CAB Glass Evaluation, Specification and Assessment With Respect To Optical-Visual Characteristics

Air Force Research Laboratory technical point of contact:
Alan R. Pinkus, Ph.D. (937) 255-8767
Date submitted: 5-30-06

1.0 Objective: Determine appropriate optical/visual parameters to specify FAA tower cab glazing with recommended specification values and measurement procedures.

2.0 Statement of Work:

- 2.1 Review existing and proposed specifications for control tower glazing with respect to optical parameters that affect vision (e.g., transmission, reflection, haze, spectral neutrality, polarization, multiple-imaging, scratches, minor optical defects, etc.).
- 2.2 Evaluate glazing and pull-down shade samples and manufacturer's specifications and compare with parameter values obtained from 2.1 above.
- 2.3 Make recommendations regarding permitted values of previously identified optical parameters and the test procedures to measure these parameters, preferably based on existing ASTM or similar standard test procedures (e.g., ASTM D1003-00 for measuring haze and transmission).
- 2.4 To the extent possible, provide information regarding the visual impact of the various optical parameters on visual performance to improve/modify existing FAA vision model.
- 2.5 Obtain from FAA any available data on current methods for periodically testing or assessing control tower glazing and pull-down shades for optical/visual quality. Use this information, if available, and the results from above sections to devise inexpensive, field usable method(s) to assess visual quality of control tower glass and pull-down shades.

3.0 Deliverables:

The primary deliverable from this effort will be a final report that includes, at a minimum, a recommended list of relevant optical parameters that should be specified, a summary of existing and proposed specifications for these parameters, recommendations with rationale for the desired minimum (or maximum as the case may be) allowed values for the identified parameters, recommended standard test procedures for these parameters, the impact of the values of these parameters on visual capability, and a summary of the testing of samples of glazing and shading materials.

APPENDIX B

Multiple Imaging Displacement QA Test Procedure (FAA Test Center)

QUALITY ASSURANCE (QA) PROCEDURE

ATCT GLASS TEST POINT DESCRIPTION
and
DOUBLE-INSULATED-GLASS UNIT ASSEMBLY TOLERANCES

1.0 Definition of Primary Viewing area of glass panel:

All measurements taken from the internal IG (insulated glass) unit spacer edges.

Bottom edge of viewing area:	6 inches up from bottom edge of the panel
Top edge of viewing area:	75 percent of the total height of the panel
Left edge of the viewing area:	10 percent of the panel width at any given point
Right edge of the viewing area:	10 percent of the panel width at any given point

2.0 Definition of QA test points on each panel:

The approved QA test using the "L" illumination method will be performed at nine test points defined below on each insulated glass (IG) unit: (see Diagram "A")

Test Point 1:	Midpoint of bottom edge of viewing area
Test Point 2:	25% height of viewing area on left edge of viewing area
Test Point 3:	75% height of viewing area on left edge of viewing area
Test Point 4:	Midpoint of top edge of viewing area
Test Point 5:	75% height of viewing area on right edge of viewing area
Test Point 6:	25% height of viewing area on right edge of viewing area
Test Point 7:	Midpoint of entire viewing area
Test Point 8:	Height = midpoint of entire viewing area Width = 25% from left edge of viewing area
Test Point 9:	Height = midpoint of entire viewing area Width = 25% from right edge of viewing area

Test points are defined as percentages of height and width due to the variable sizes and shapes of IG units required at Air Traffic Control Towers. (See Diagram "A")

3.0 Number and Timeframe of QA Tests:

In order to ensure the final installation of IG units with acceptable imaging quality, the approved QA Procedure using the "L" illumination method will be performed at these specific time frames:

1. Perform one QA test per IG unit at the point of manufacture, prior to crating for shipment.

2. Perform one QA test per IG unit at the Air Traffic Control Tower installation location after removal of shipping materials, but prior to being lifted by crane for installation in the ATCT cab.

3. Perform one QA test per IG unit after completion of installation in the ATCT tower cab, to include the final torque of window frame set screws.

4.0 QA/Acceptance Test Procedure:

4.1 Illuminated "L" Image:

Observations will be made by observing a reflection, incident to the panel surface, and using a flashlight with an illuminated "L" shaped image. Dimensions of the "L" are as follows: 20mm total height, 8mm total leg length, 3mm body width. The vertical body and 6mm of the 8mm leg of the "L" will be colored red.

4.2 Illuminated "L" Test Method:

Observations will be made at an observer distance of two meters from the panel. Reflections shall be observed at the nine test points described in Para. 2.0 above. The "L" shaped double image shall be rotated such that the short legs of the "L" are aligned along a common axis. The illuminated "L" shaped image is depicted in Figure B-1.

Acceptable divergence tolerances between the glass panes will be observed when the properly aligned legs of the "L" image either touch or overlap, depending on the specific test point measured. Observed double images on the test points within the boundary of the Primary Viewing Area must be observed as a significant overlap (approx. 2mm) of the aligned leg of the "L". The red colored area of the "L" image is calibrated to the manufacturing tolerance of the Primary Viewing Area. No white light should be observed in the area of overlap of the two "L" images.

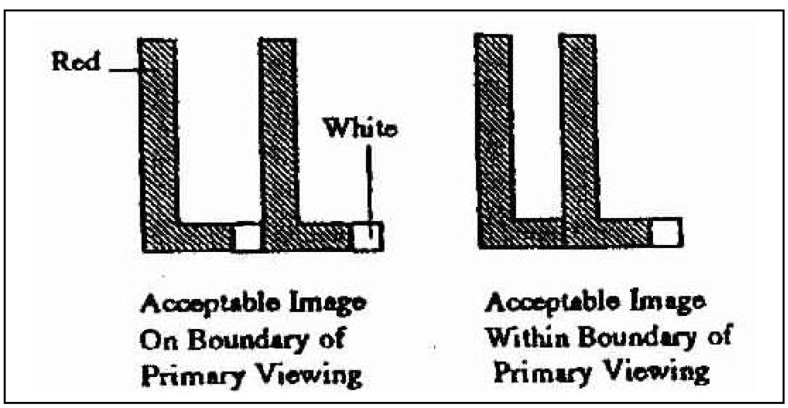


Figure B-1. Illuminated "L" shaped image.

Observed double images at the testing points on the boundary of the Primary Viewing Area must at least be observed to have the aligned legs of the “L” touch. This may result in the acceptable viewing of the white section of the leg of the primary image touching the red body of the “L” of the secondary image. Any separation of the images, when legs are properly aligned, shall constitute failure of that specific test point.

For test points on the boundary of the Primary Viewing Area, three or more test point failures occurring at Test Points 1, 2, 3, 5, and 6 shall cause the panel to fail the QA test and be classified as an unacceptable glass panel.

NOTE: Acceptance criteria is derived from the test data for a marginally acceptable panel. Of the 20 test points identified during the double imaging tolerance measurement tests at the FAA Technical Center, 30 percent fell outside the fully acceptable limits for deflection when measured on a “Marginally Acceptable” pane. The test points exceeding fully acceptable deflection thresholds were always located on the outer edge of the panel. Therefore, a less stringent tolerance is proposed for areas of the IG unit along the boundary of, and outside the defined “Primary Viewing Area”.

QA TEST POINTS LAYOUT

TYPICAL PANE

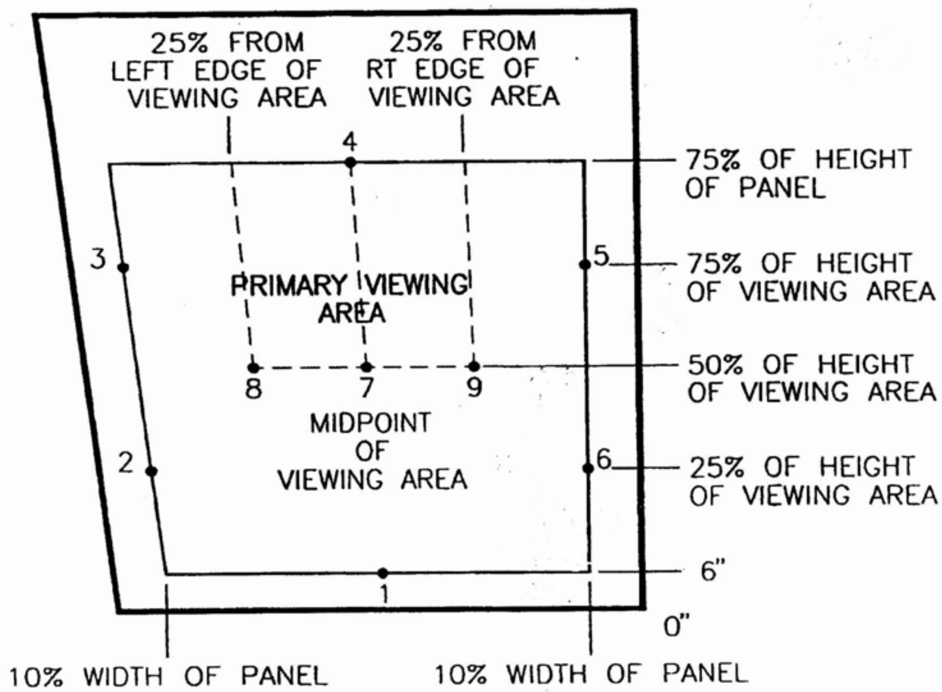
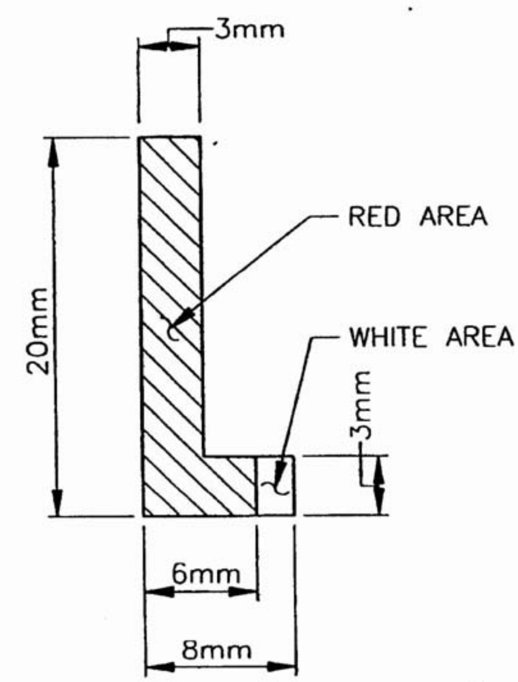


IMAGE DEFLECTION MEASURED AT 2 METERS
WITH ILLUMINATED "L" SHAPED IMAGE

DIAGRAM A

:/15/96



NOTES:

- TO BE USED AT 2 METER OBSERVER DISTANCE FROM PANE OF GLASS:
- SEPERATION = UNACCEPTABLE
- WITHIN PRIMARY VIEWING AREA = ALIGNED IMAGES OVERLAP WITH NO WHITE OBSERVABLE
- ON BOUNDARY OR OUTSIDE PRIMARY VIEWING AREA = ALIGNED IMAGES TOUCH

DIAGRAM B

2/15/96

APPENDIX C

Double Imaging in ATCT Glazing: History of FAA "L" Test and Double Image Formation Analysis

The objective of this appendix is to provide some background and a short analysis of the "L" pattern multiple imaging test developed for the FAA by Fluor Daniel, Inc. The actual complete "L" test description, as obtained from the FAA, is found in Appendix B.

According to D. R. Goodall (1998) and information obtained from Jack McNamee of FAA (personal telecon 5/18/2007), the "L" pattern test was devised in response to objectionable multiple images seen at night in the cab glass due to an electromagnetic interference (EMI) coating that was added to the glazing. As improved weather radars were installed at some airports to better detect windshear, electromagnetic interference with the ATCT cab was experienced. One standard way to block this type of electromagnetic interference is to enclose the cab in a conductive shell. This meant the windows needed to be coated with a conductive material to block the radiated electromagnetic energy, thereby reducing or eliminating the EMI.

Goodall reports that Fluor Daniel, Inc. selected a Tempest Security Systems, Inc., product called Datastop as the best product available to achieve the objective. Note that Datastop is a product of Pilkington and is distributed by Tempest Security Systems. According to the Tempest Security Systems, Inc., web page, there are several glass products that are under the Datastop name, each with different transmission and reflection characteristics. However, because of the very nature of this type of coating, the reflection characteristics of all the products are higher than the reflection one would expect from plane glass surfaces.

Table C-1. Optical characteristics of Datastop products from Tempest Security Systems.

Optical Properties									
		Light		Solar Radiant Heat					U value
Code	Colour from Outside	Trans-mittance	Reflect-ance	Direct Trans-mittance	Reflect-ance	Absorp-tance	Total Trans-mittance	Total Shading Coefficient	(W/m^2K)
D60	Gold	0.45	0.35	0.19	0.40	0.41	0.29	0.33	1.35
D50	Neutral	0.68	0.17	0.39	0.20	0.41	0.52	0.60	1.40
D45	Grey	0.23	0.11	0.11	0.16	0.73	0.21	0.24	1.35
	Bronze	0.27	0.13	0.12	0.18	0.70	0.22	0.25	1.35
	Blue	0.29	0.15	0.12	0.18	0.70	0.22	0.25	1.35
	Green	0.39	0.23	0.12	0.18	0.70	0.22	0.25	1.35
D40	Neutral	0.70	0.18	0.48	0.13	0.38	0.59	0.67	2.05
L60	Gold	0.39	0.40	0.21	0.43	0.36	0.29	0.33	3.15
L45	Neutral	0.68	0.13	0.48	0.17	0.35	0.56	0.64	3.15
L40	Neutral	0.74	0.13	0.50	0.10	0.40	0.59	0.68	3.10

Table C-1 is from the Tempest Security Systems, Inc., website showing the characteristics of their different Datastop products. A personal telephone conversation with Ian Waterman of Tempest Security Systems, Inc., revealed that the table is out of date and that not all of these products are currently available. According to Mr. Waterman, the product used in a dozen or so FAA towers in the 1990's timeframe had a transmission coefficient of 0.68 and a reflection coefficient of 0.17. It was also noted that

the conductive EMI coating was on the inside surface of the cab window (surface #4) counting from the outside of the cab. It appears that the product that was used in these towers was the second line item, D50, based on the transmission and reflection values. Further discussions with Mr. Waterman indicate the "D" products mean they are "double glazed" (two panes of glass with an air gap) and the "L" products stand for "laminated." The current spec for the double glazed Datastop product is 70% transmission and 17% reflection. The laminated product (L40 in the table) still has a transmission value of 74% and a reflection value of 13%. The Datastop product in a single piece of glass 6mm thick has a transmission value of 82% and a haze value of 0.7%; the reflection value was not provided but is almost certainly higher than the 8% value expected for uncoated glass.

One story is that it was this increased reflectance coefficient that increased the secondary image intensity seen at night to a level that it was noticeable and objectionable. It should be noted that all glazing, single or double, has multiple images caused by multiple reflections between the various surfaces. A second story (from Ian Waterman) is that the multiple imaging issue was added to the EMI problem as simply another ATCT cab glass issue that needed to be addressed. In either case, a means was needed to mitigate the multiple-imaging problem.

If the glass surfaces are perfectly flat and parallel and one is observing distant objects at night through the glazing, then the various images are formed essentially on top of the primary image of the object and are not noticed. However, if the glass surfaces are not parallel, then several of these images will appear at some angular displacement from the primary image. If these images are not very intense, then they might well be ignored by the observer. However, if the secondary images are too intense (and angularly displaced), then they may be objectionable.

As a matter of interest, this very same problem of multiple images has been seen in military aircraft windscreens when they transitioned from thin, glass windscreens to fairly thick, curved, multi-layered plastic windscreens. Most notably, the F-111 and the B-1B both demonstrated multiple-image effects in *some* of the windscreens that the pilots found objectionable. A study of the B-1B windscreens that pilots objected to and the windscreens that they did not object to resulted in the conclusion that the primary factor separating these two categories of windscreens was the amount of angular separation between the primary and the secondary images[13]. A test method was devised (ASTM Standard Test Method F1165-98)[5] to measure the angular separation between the primary and secondary images. This test method made use of light sources on one side of the windscreen and a camera on the other side of the windscreen and is therefore not suitable for measuring the ATCT cab glass *in situ*. However, the fundamental parameter addressed in both of these tests (the ASTM test and the "L" test) is the same, as will be explained later.

For double-glazed windows, tracking the various light ray paths that cause the multiple images is somewhat complicated. Some light is reflected from *each* of the four surfaces of the two panes of glass. Figure C-1 shows schematically some of the reflection paths for a single, uncoated pane of glass.

A light source on the right emits a ray of light that is 100% as it impinges on the first surface of the glass. This surface has a reflection coefficient of *R1* and a transmission coefficient of *T1*. For simplicity, it is assumed that the glass does not scatter nor absorb light so the transmission and reflection coefficient of each surface must total to unity (a value of 1.00). For ordinary glass, the transmission coefficient would be approximately 0.96 and the reflection coefficient would be about 0.04 for this first surface. For reasons beyond the scope of this appendix, the transmission and reflection coefficients of plane glass would be the same for both of the surfaces shown.

Using this information, it is now possible to calculate the intensity of the primary light ray (image) denoted by the ray numbered "1" in Figure C-1 and the secondary ray ("2") plus the tertiary ray ("3"). There are actually many more rays but the intensity of each succeeding image is lowered to a point where it can be ignored.

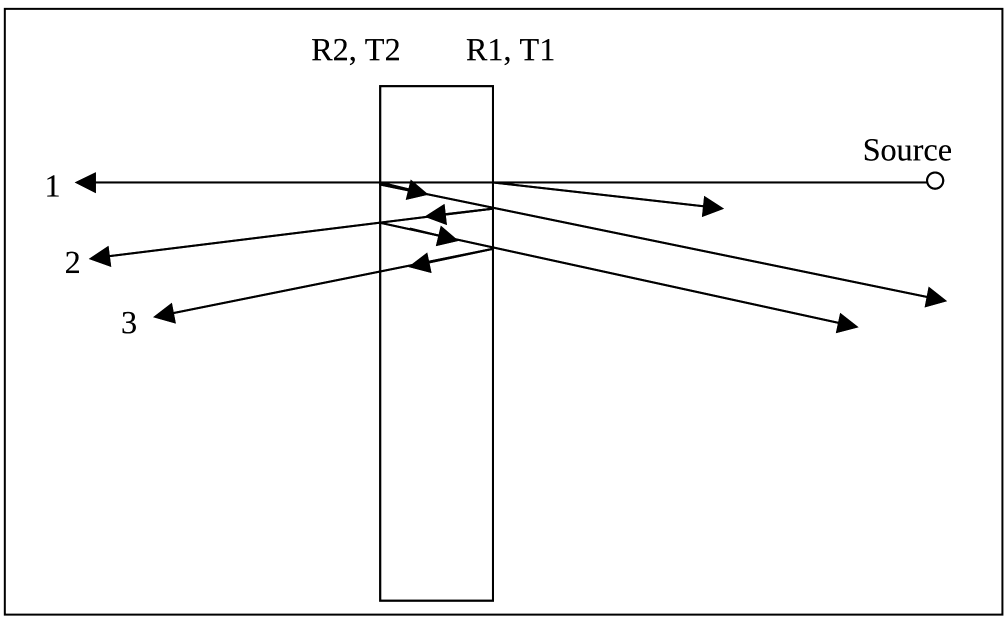


Figure C-1. Schematic diagram of the formation of multiple images in a single pane of glass.

From Figure C-1, one can see that the ray from the source must pass through both surfaces. The amount of light that gets through each surface is determined by the transmission coefficient. Therefore, 0.96 of the light gets through the first surface and then 0.96 of this amount gets through the second surface. So, the intensity of the primary image (ray "1") is 0.96 times 0.96 or about 0.92 of the incident ray.

Ray number two is a bit more complicated. It is transmitted by the first surface (factor of 0.96) reflected by the next surface (0.04) and then reflected again by the first surface (0.04) and finally transmitted out of the second surface (0.96). Therefore, its intensity compared to the original incident ray is 0.96 times 0.04 times 0.04 times 0.96 or about 0.0015. This value is *much* lower than the primary image (ray "1") and is therefore fairly

easily ignored. The ratio of primary image intensity to the brightest secondary image is 0.96/0.0015 or about 651 to 1.

According to Ian Waterman of Tempest Security Systems, the innermost surface (inside the cab) was the surface coated with the Datastop EMI protection coating. The overall product transmission and reflection coefficients are listed in Table C-1, the D50 row. Based on the overall product having the listed reflection and transmission values and knowing which surface was coated, it is possible to make a reasonable estimation of the reflection and transmission values for the Datastop surface alone. It is then possible to calculate what the primary- to secondary-intensity ratio is of a single pane of EMI coated glass. This gives a primary to secondary ratio of about 260 to 1; still a fairly good ratio but not as good as the uncoated glass.

This secondary-reflection analysis gets far more complicated with insulated glass that has two sheets of glass separated by an air gap. The following figure shows a schematic of the different first order reflection passes through this type of glazing.

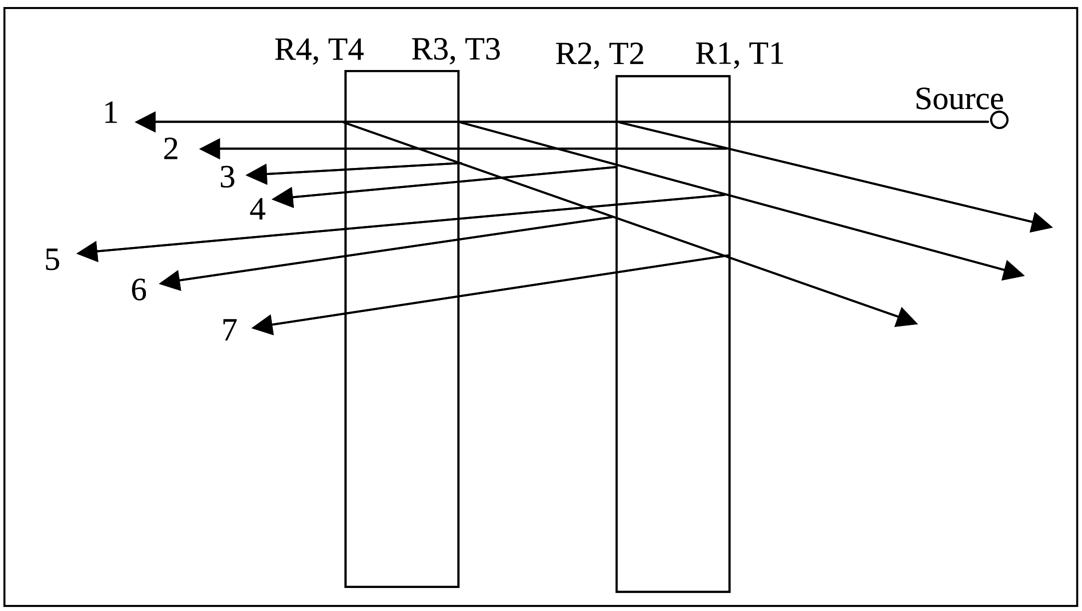


Figure C-2. Schematic diagram of multiple imaging pathways for double glazed windows.

The reflection *angles* shown in Figure C-2 don't really exist. They were introduced in order to make it easier to follow the different reflection pathways. If the two sheets of glass have perfectly parallel sides and are aligned parallel to each other, then *all* of these ray paths fall exactly on top of each other and the secondary reflected images would fall essentially on top of the primary image, thus causing no offending visual effects.

Potentially offending visual effects occur when the two sheets of glass are not parallel. If the glass on the right were tilted with respect to the glass on the left, then ray path number 3 would still fall directly on top of the primary image ray number 1. However, all of the other secondary reflection ray paths would fall on top of a secondary image.

The same type of analysis can be done for this case to calculate a ratio between the separated images (the primary image intensity plus any reflected images that fall directly on the primary image compared to all of the other first order secondary reflection paths). The result achieved from this analysis depends on which surface has the EMI coating. Using the estimated values, it can be determined that the ratio is about 47 to 1 if surface #2 has the EMI coating, about 63 to 1 if surface #3 is coated and about 85 to 1 if surface #4 (the surface exposed to the interior of the cab) is coated. It is most likely for this reason that Pilkington selected this surface to receive the EMI coating as it produced the least intensity for the secondary image compared to the primary.

All of these ratios are still fairly high, but at night, this means the secondary image of a light source target would be easily visible *if* the tilt angle between the two sheets of glass is sufficient to significantly separate the two images. Note that a laminated product with no air gap should essentially eliminate this multiple imaging separation problem.

This brings us to the second parameter that can be used to characterize multiple imaging, which is the angular separation between the primary image and the secondary image. If this angle is very small (or zero), then the secondary image is not separated sufficiently from the primary image to be objectionable. It is this angular separation between the primary and secondary image that is tested with the “L” pattern. Figure C-3 shows the ray paths for the primary and secondary images that occur when viewing a distant light source through a pane of glass that does not have parallel sides (the ray paths are essentially identical to those that would occur with insulated glazing which has an air gap between the two sheets of glass). Note that the angular separation that is perceived between the primary and secondary images is twice the angle of tilt between the two sides of the glass (or the two sheets of glass in the case of insulated glazing). This means the double image angular separation effect is very sensitive to the tilt angle between the two surfaces (or two panes of glass for the insulated glass case).

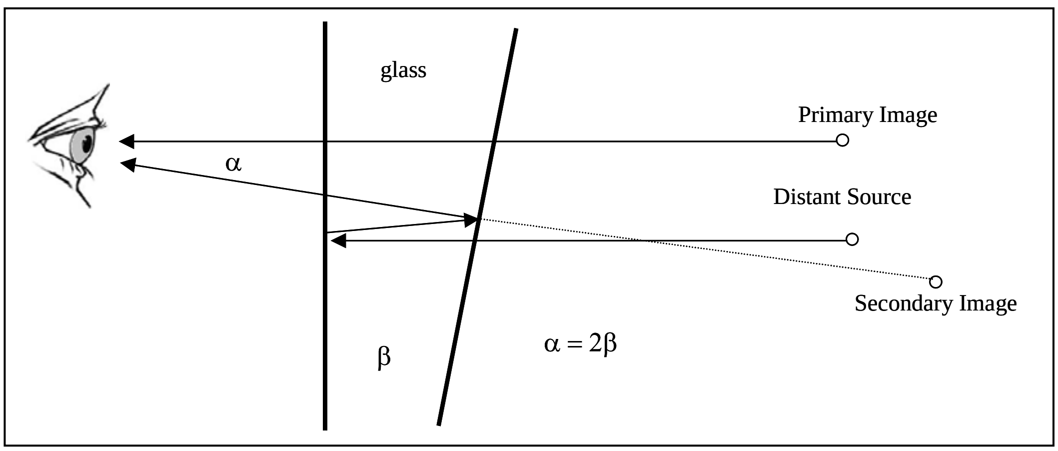


Figure C-3. The relationship between the apparent angular separation between the primary and secondary images (label α) and the angle of tilt between the two glass surfaces (label β).

Because the target light source and the observer are on the same side of the glazing for the "L" test, the apparent angular separation of the two images observed is exactly equal to the tilt angle (not twice the tilt angle). The description for the "L" test is found in Appendix B and is not repeated here. It is possible to use essentially the identical procedure as described in the "L" pattern test but modify the target pattern from an "L" to a simple disc of light (such as a hole drilled in an opaque plate covering a flashlight). The diameter of the disc would be 6mm or 8mm for the primary viewing test points and the boundary viewing test points respectively (see the "L" test in Appendix B). There are two minor advantages of using this as the target pattern: 1) it is easier to make and 2) one does not have to orient the flashlight such that the legs of the "L" reflections are aligned (see "L" test in Appendix B). A disadvantage is that two flashlights or two covers are needed to put over the one flashlight to test the two different types of viewing test points (primary and boundary).

Another advantage of the disk light test is that it is a little easier to produce a figure to describe the effects of this test and the potential sources of error (which are identical to the "L" test). Figure C-4 shows the reflection test using a disk light source. The two virtual images produced by the mirror-like reflections from the two surfaces are not only angularly displaced because of the tilt of the outside surface, but they also appear at slightly different distances because of the different distances from the light source to the reflecting surfaces.

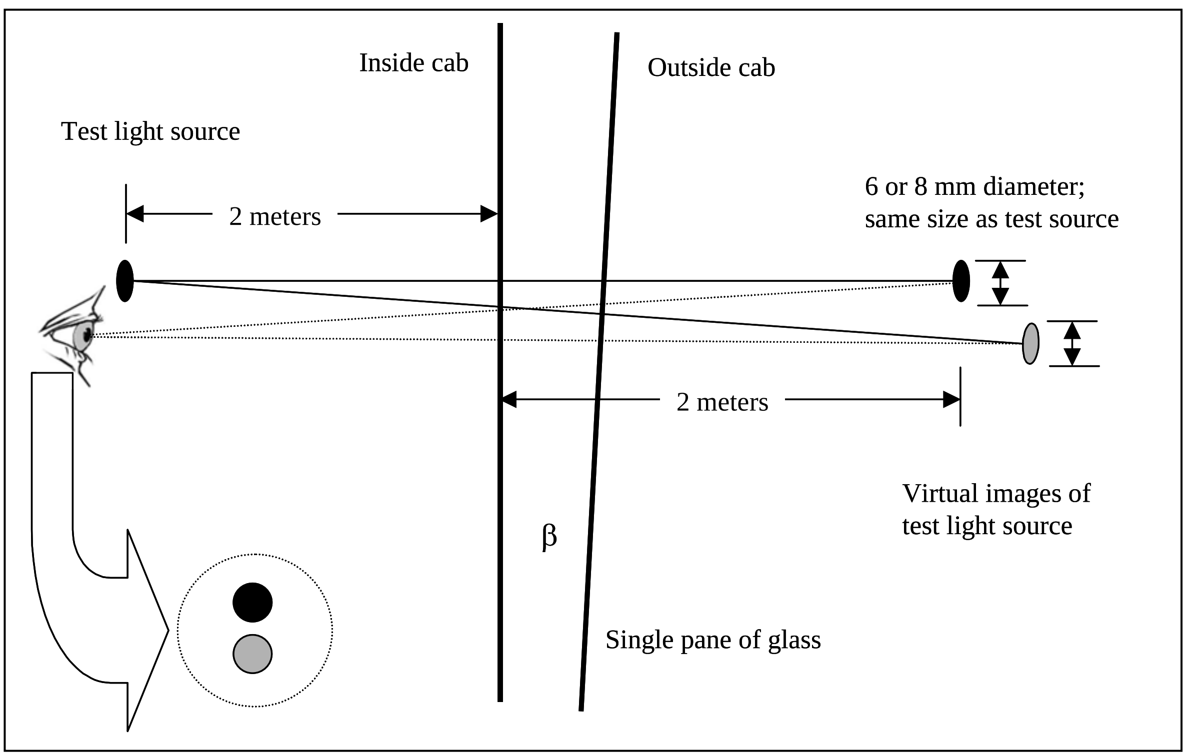


Figure C-4. Schematic of reflection test using a disk light source instead of an "L" pattern. The large arrow points to what the observer would see in this case.

As can be seen from Figure C-4, the two reflections are at slightly different distances from the observer. The magnitude of this difference in distance depends on the size of the air gap for the insulated glass case and the thickness and index of refraction of the inner pane of glass. Assuming the inner pane of glass has an index of refraction of 1.5 and the thickness of the air gap and the thickness of the inner pane of glass are both ½ inch, it is possible to show that the reflecting surface is an optical distance of about 2.0212 meters from the light source and the virtual image would be twice that or about 4.0424 meters away. This means the two virtual images are separated (longitudinally) by a distance of about 42.4mm.

This longitudinal difference in the images can be a source of error when making observations of the "L" pattern (or disk pattern) light source reflections. The two different image distances give rise to the potential for parallax, which can make the two disks (or legs of the "L") appear closer together or further apart depending on which direction the observer views the reflections. The further off-axis the observer is, the greater the error. Figure C-5 demonstrates this potential for error.

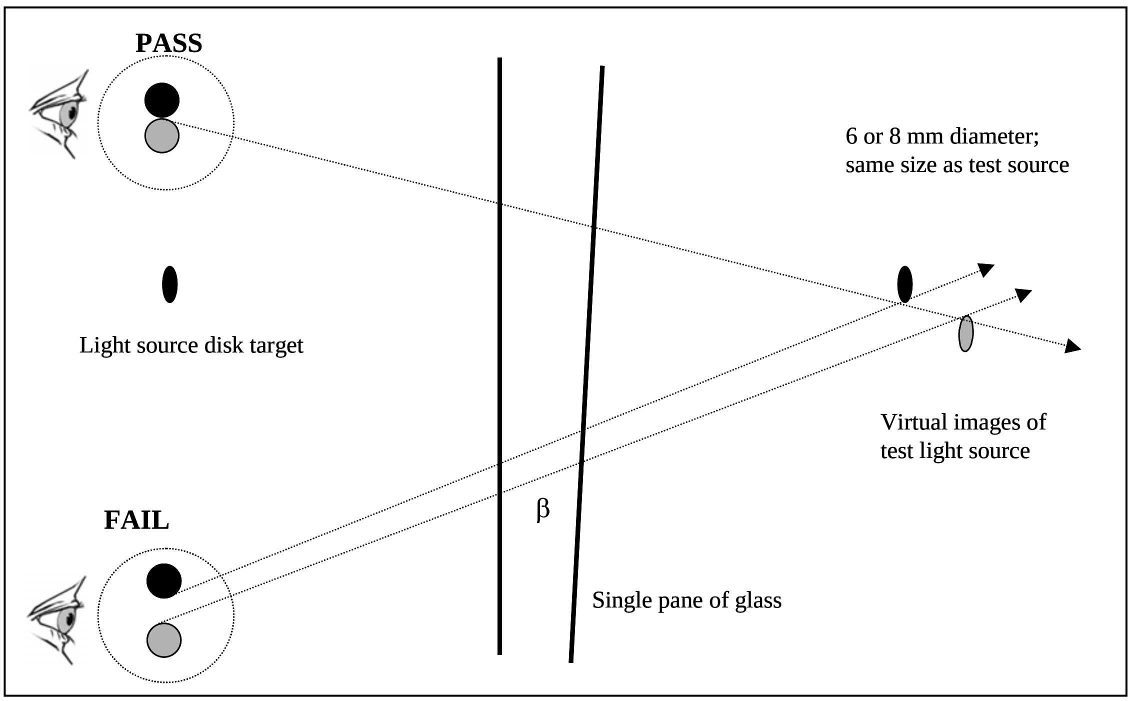


Figure C-5. Schematic drawing showing the potential for error in reflection measurement for the "L" pattern test.

Using the previous example values for the air gap, window thickness, and index of refraction (½ inch, ½ inch, and 1½, respectively), it is possible to calculate the amount of error as a function of the distance the observer is away from the axis of the target pattern. Table C-2 is a summary of this error. The error values are given in millimeters (mm) that correspond to the error in distance observed between the centers of the two target pattern reflections (results are the same for the "L" pattern and the disk pattern).

Table C-2. Error amounts for off-axis viewing of "L" test.

Off-axis Distance	Error	6mm spec	8mm spec
d (mm)	e (mm)	% error	% error
50	0.53	8.8	6.6
100	1.06	17.6	13.2
150	1.59	26.5	19.8
200	2.12	35.3	26.5
250	2.65	44.1	33.1

The criteria value stated in the "L" pattern test is a separation of the reflected images of no more than 6mm for the primary viewing area and no more than 8mm for the boundary viewing area. It is possible to calculate the approximate angular separation of the images as viewed from the 2-meter testing distance. The 6mm criterion value corresponds to about 5.2 minutes of arc, and the 8mm criterion value corresponds to about 6.9 minutes of arc. These are the maximum allowed tilt angles between the two reflecting surfaces (e.g., the inner and outer panes of glass in an insulated product) for the two identified viewing zones. The observed angular separation of the primary image from the secondary image for objects viewed outside the cab equal twice the tilt angle between the glass surfaces. This means the secondary image will appear a maximum of 10.4 arc minutes away from the primary image in the primary viewing area and 13.8 arc minutes away for the boundary viewing area.

APPENDIX D

Excerpt from FAA document: 08800 GLAZING Rev. 3

PART 2.00 PRODUCTS

2.03 INSULATING GLAZING UNITS:

B. Glazing units shall meet the following requirements:

Type "II"

Special glass unit for ATCT cabs. Glass shall meet ASTM C1036-06 Quality Q1 clear ½-inch thick float glass produced by a single source, from the same lot, and shall bear the mark of the manufacturers. Edges shall be factory cut and ground smooth. Insulating glass units for the ATCT cab shall be hermetically sealed units with the two lights of glass separated by a dehydrated air space. The metal separator shall be dark bronze color. Units shall be double sealed: primary seal shall be polyisobutylene; secondary seal shall be polyurethane or silicone. Within the bottom of 1/3 of one of the vertical edges of the units, the fabricator shall install an open 12-inch long capillary/breather tube for pressure equalization. The tube shall be open during installation. Glass glazing unit shall meet the following requirements:

Outer Pane	½" thick, clear
Inner Pane	½" thick, clear
Total Overall Thickness	1½" thickness
Visible Transmittance	65 percent

PART 3.00 EXECUTION

3.03 INSTALLATION OF GLAZING MATERIAL:

A. CAB GLASS:

Install with breather tube open. Position the end of the tube so that the end of the tube is visible and accessible when the exterior glazing bead cover is removed. Use caution while positioning the tube not to break the seal of the tube at point of penetration of the insulation glass unit. Before installing the glazing bead cover, seal the end of the tube with polyurethane sealant in a manner that the seal can be easily broken. Provide a weatherproof decal adhered to the bead cover as indication of the location of the breather tube. This special requirement is to permit periodic future air pressure equalizing.

3.04 FIELD QUALITY CONTROL:

A. Replace glass and materials that become broken, chipped, cracked or damaged during construction and before substantial completion of building.

B. Where existing work is required to be re-glazed, remove existing setting material completely to base glazing frame and re-glaze opening as required for a new glazing.

C. Surface scratches shall be cause for rejection of any piece of glass. Deposits, iron spots, weld marks, or any defects that confuse vision from cab shall be defects that require replacement of glass.

LIST of ACRONYMS and ABBREVIATIONS

AFRL/HECV – Air Force Research Laboratory/Battlespace Visualization Branch
ASTM – American Society for Testing and Materials
ATC – Air Traffic Control
ATCT – Air Traffic Control Tower
Cab – a control cabin
cd/m^2 – candela per square meter
EMI – Electromagnetic Interference
FAA – Federal Aviation Administration
fL – foot-Lamberts
IG – insulated glass
IGU – Insulated Glass Unit
IND – Indianapolis
low-E – low emissivity
mm – millimeters
NFRC – National Fenestration Rating Council
NVGs – Night Vision Goggles
PVB – Polyvinyl Butyral
QA – Quality Assurance
SOW – Statement of Work
US – United States
USAF – United States Air Force
ZGI – Zamil Glass Industries